LA-UR- 04-4335

Approved for public release; distribution is unlimited.

Title: Cosmic Ray Muon Radiography for the Detection of Contraband SNM (U)

Author(s): Larry SCHULTZ, Konstantin BOROZDIN, Thomas ASAKI, Richard CHARTRAND, Nicholas HENGARTNER, Gary HOGAN, Christopher MORRIS, William PRIEDHORSKY, Richard SCHIRATO, Matthew SOTTILE, Kevin VIXIE, Brendt WOHLBERG

Submitted to: IAC Active Interrogation Workshop, 2004,
Idaho Falls, Idaho,
June 29, 2004.

Los Alamos
NATIONAL LABORATORY

Cosmic Ray Muon Radiography for the Detection of Contraband SNM

Larry SCHULTZ*, Konstantin BOROZDIN, Thomas ASAKI, Richard CHARTRAND, Nicholas HENGARTNER, Gary HOGAN, Christopher MORRIS, William PRIEDHORSKY, Richard SCHIRATO, Matthew SOTTILE, Kevin VIXIE, Brendt WOHLBERG

Los Alamos National Laboratory, Los Alamos, NM 87545

and

Gary BLANPIED

Department of Physics and Astronomy, University of South Carolina, 712 Main Street, Columbia, SC 29208

ABSTRACT

Highly penetrating cosmic ray muons shower the Earth at the rate of 10,000 $m^{-2}\cdot min^{-1}$ at sea level. In our previous work (Nature 422, p 277 (2003); Review of Scientific Instruments 74(10). pp 4294-7 (2003); Nuclear Instruments and Methods A 519, pp 687-694 (2004)) we presented a novel muon radiography technique which exploits the multiple Coulomb scattering of these particles for nondestructive inspection without the use of artificial radiation. High Z / high density materials deflect muons much more strongly than do lower Z, lower density materials, providing for an information source that is sensitive to SNM and shielding material. We have demonstrated the technique with a small scale prototype and via Monte Carlo simulation are investigating the feasibility of using it for the detection of SNM/shielding in vehicles and shipping containers. Simulated tests suggest that detection of modest sized high-Z objects within medium-Z backgrounds in minute order exposure times may be achievable. We are constructing a large scale prototype for experimental confirmation of these simulations. A significant benefit of this technique is that inspection of manned vehicles can be performed since no artificial radiation is applied.

* Corresponding author: email: Schultz@lanl.gov, voice phone: (505) 667-9431.

Cosmic Ray Muon Radiography for the Detection of Contraband SNM

Larry Schultz
Los Alamos National Laboratory

June 29, 2004

2004 Active Interrogation Workshop
Idaho Falls, Idaho

$\mu^{\pm}$

Collaborators

- Project Leaders
  - C.L. Morris (P-25), W.C. Priedhorsky (ISR-DO)
- LANL P, ISR, X, CCN, T Divisions
  - T.J. Asaki, K.N. Borozdin, R. Chartrand, J.J. Gomez, N.W. Hengartner, G.E. Hogan, A. Saunders, L.J. Schultz, R.C. Schirato, M. Sottile, K.R. Vixie, B. Wohlberg.
  - M.E. Teasdale, M.Q. Cannon, J.J. Medina (students)
- University Collaborators
  - A. Fraser (Portland State University)
  - G. Blanpied (University of South Carolina)
  - J. Katz (Washington University in St. Louis

Overview

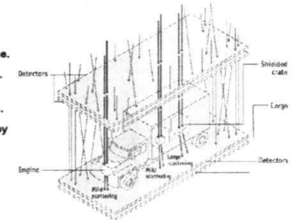
- Problem Description
- Cosmic Ray Muon Radiography Background
- Experimental Demonstration & Simulation
- Contraband Detection Approaches
- Mid-Scale Demonstration Plan
- Summary / Path Forward

Contraband Problem

- Smugglers may try to bring in a variety of threat material such as U, Pu, or radioactive material.
- To get past gamma ray detectors, these items will need to be shielded, so there will also be lead or other high Z shielding material. Question: How much shielding?
- A characteristic of high Z material is that charged particles will experience much more multiple scattering as they traverse them then when going through lower Z material.
- So our proposed method of detecting U, Pu, or shielding material is to measure the multiple scattering of charged particles (passive cosmic ray muons, in fact) that pass through a cargo container or vehicle.

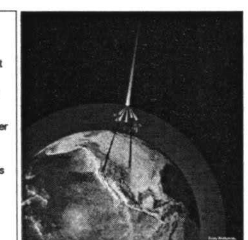
Potential Advantages of Muon Radiography

- **No artificial radiological dose.**
- **No artificial source required.**
- **Low-cost muon detectors have been used for decades.**
- **3D reconstruction enabled by multi-angle "illumination."**
- **The heavier the shield the better.**



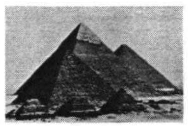
Cosmic Ray Muons

- Primary cosmic rays strike the atmosphere and generate a cascade of secondary particles.
- Muons are the dominant particle at the Earth's surface.
- Most muons can penetrate tens of meters of rock or more.
- Muons arrive at a rate of 10,000 per square meter per minute (at sea level).
- The spectrum of cosmic ray muons (energy, arrival angle) is well documented. Peak at 3 GeV.
- Cosmic ray muons arrive from upper hemisphere but tend to be downward directed because of atmospheric shielding.



Differential Attenuation Radiography

Searching for Hidden Chambers in Pyramids



Luis Alvarez, et. al.
Science **167**, 832 (1970)

Arturo Menchaca, et. al.
current effort, see

http://www.msnbc.msn.com/id/4540266/

Predicting Volcanic Eruptions

Tanaka, Nagamine, et. al.
Nuclear Instruments and Methods A
507:3, 657 (2003)

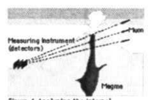
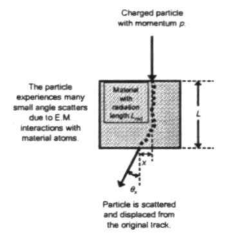


Figure 4: Analyzing the internal structure of a volcanic zone using muons

Los Alamos
NATIONAL LABORATORY

Multiple Scattering



Distribution of scattering angle is approximately Gaussian:

$$f_{\theta_x}(\theta_x) \cong \frac{1}{\sqrt{2\pi}\sigma_\theta} e^{-\frac{\theta_x^2}{2\sigma_\theta^2}}$$

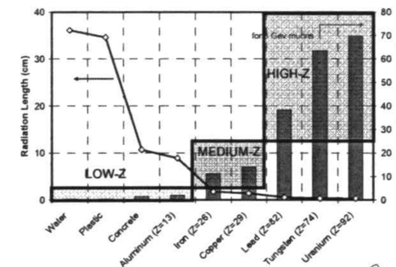
Standard deviation is related to the material:

$$\sigma_\theta \cong \frac{15}{p}\sqrt{\frac{L}{L_{rad}}}$$

The *radiation length* L_0 is a characteristic property of material that generally DECREASES with INCREASING material Z number.

Los Alamos
NATIONAL LABORATORY

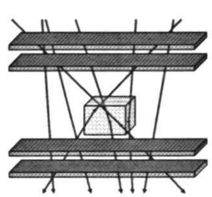
Scattering is Material Dependent



Los Alamos
NATIONAL LABORATORY

The Basic Concept

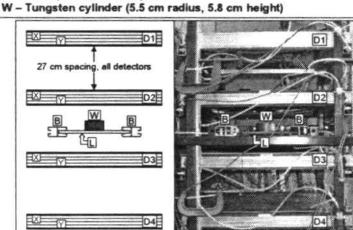
- Track **individual** muons (possible due to modest event rate).
- Track muons **into** and **out of** an object volume.
- Determine scattering angle of each muon.
- Infer Z-level of material within volume from data provided by many muons.
- New tomographic reconstruction algorithms are required.



Los Alamos
NATIONAL LABORATORY

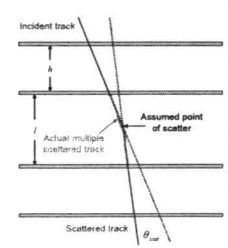
Experimental Prototype

- D1-D4 – Muon detectors (drift chambers, measure X/Y position)
- B – "Unistrut" beams
- L – Lexan plate to hold objects
- W – Tungsten cylinder (5.5 cm radius, 5.8 cm height)



Los Alamos
NATIONAL LABORATORY

Reconstruction – Localizing Scattering

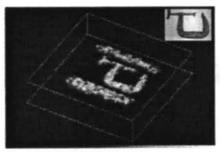


- Assume multiple scattering occurs at a point
- Find point of closest approach (PoCA) of incident and scattered tracks
- Assign scattering signal to voxel containing PoCA
- Since detectors have known position uncertainty, signal may be spread over voxels relative to PoCA uncertainty.
- Simply add localized scattering signals for all rays.

Los Alamos
NATIONAL LABORATORY

Experimental Radiographs

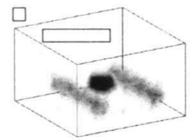
A Steel C-Clamp



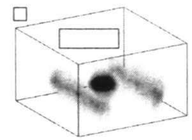
LANL of Lead

Experiment and Simulation

Experiment

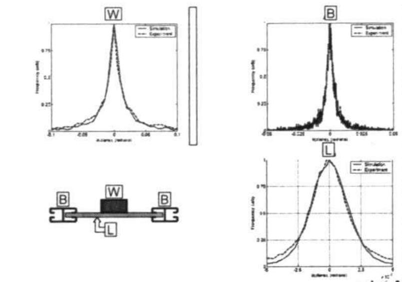


Simulation



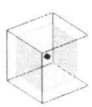
Standalone Monte Carlo muon transport simulation developed.
GEANT 4 based simulation has also been tested.
MCNPX based simulation is under development.

Scattering Histograms

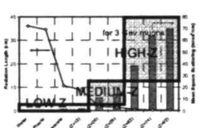


PoCA works well for...

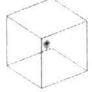
Scenes with relatively small isolated objects



Simulated scene
1x1x1 m³ Fe box (3 mm wall thickness)
4 cm radius U sphere in center

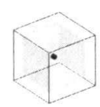


PoCA Reconstruction
~ 1 minute of simulated exposure

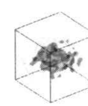


PoCA works less well for...

Scenes with large, distributed, or multiple objects

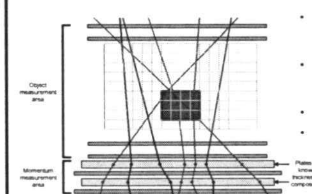


Simulated scene
1x1x1 m3 Fe box (3 mm wall thickness)
now filled with solid Aluminum
and 4 cm radius U sphere in center



PoCA Reconstruction
~ 1 minute of simulated exposure

Momentum Estimation



- Measuring particle momentum increases confidence in material inference.
- One method is to estimate momentum from scattering through known material.
- With 2 plates $\Delta p/p$ is about 50%.
- With N measurements $\Delta p/p$ approaches:

$$\sqrt{\frac{1}{2N}}$$

Simulated Scenarios

- Vehicle / Container
  - 6 x 2.4 x 2.4 meter cargo container (3 mm steel walls).
  - No POV's or vehicle components simulated yet.
- Objects
  - No SNM object
  - Uranium sphere (6 cm radius, 20 kg)
  - Pu sphere (4 cm radius, 5 kg)
  - Lead Cylinder (5 cm rad, 10 cm tall) filled with 800 g of Pu.
  - 1700 kg (r = 40 cm) and 350 kg (r = 20 cm) Fe spheres.
- Backgrounds
  - Otherwise empty container.
  - 11 metric tons of Iron distributed throughout the container.
  - 14 metric tons of half density Fe spheres (auto differential proxies).
  - Random (air-medium Z) 50 x 50 x 50 cm³ cubes (new, no results yet).

Steps in Detection

- First, is there something interesting?
  - Almost all vehicles contain harmless cargo and should be cleared quickly.
- Second, is the interesting item a threat?
  - If there is something generating a lot of scattering, is it a big piece of steel or a smaller piece of lead or SNM?
- Third, where is it and what does it look like?
  - To decide what to do next, we would like more information on object size, shape, location, etc.

Many analysis techniques have been tested to address these questions. I will highlight three of them.

Los Alamos NATIONAL LABORATORY

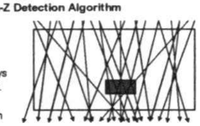
IS THERE SOMETHING OF INTEREST? Ray Crossing Algorithm

Ray Crossing High-Z Detection Algorithm

Apply a bend angle cut. Keep only high bending rays.

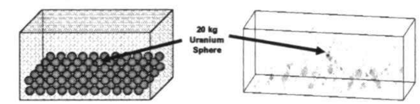
Apply an approach cut. Keep only rays which approach one another closely.

Create 3D histogram of the approach locations.



Uranium amongst automobile differentials

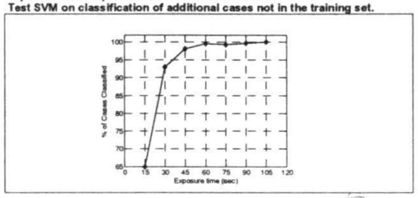
Signal map -- 60 seconds exposure



Los Alamos NATIONAL LABORATORY

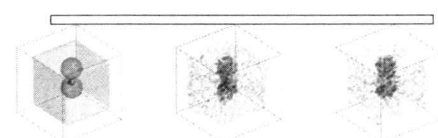
IS IT A THREAT? Support Vector Machine Classification

- Threat object: 20 kg Uranium sphere.
- Background: varied from empty container to more than 10 tons of iron.
- Train SVM by providing scattering data for simulated threat / non-threat cases.
- Require that SVM DETECT all threats. Measure the performance by the exposure time required to REJECT non-threats.
- Test SVM on classification of additional cases not in the training set.



Los Alamos NATIONAL LABORATORY

WHAT DOES IT LOOK LIKE? Maximum Likelihood Tomographic Reconstruction



Objects
1x1x1 m³ Fe box (3 mm walls)
Two half density Fe spheres (automobile differentials)
20 kg U sphere

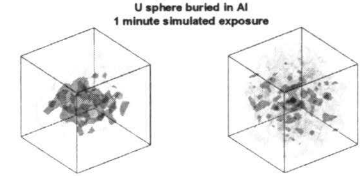
ML reconstruction
1 minute exposure

ML reconstruction
No U sphere

Los Alamos NATIONAL LABORATORY

ML/EM a Big Improvement over PoCA

Previous scene
U sphere buried in Al
1 minute simulated exposure

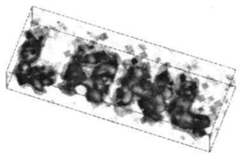


PoCA Reconstruction

ML/EM Reconstruction

Los Alamos NATIONAL LABORATORY

ML/EM on Experimental Data



A good start but a bit messy.
Quantum errors in track reconstruction are part of the problem.
More work is needed to properly model experimental error.

Los Alamos

Contraband Detection Summary

- **Encouraging results for a variety of simulated test cases, suggesting feasibility of:**
  - Clearing low-Z cargo quickly.
  - Identifying modest sized high-Z contraband within low to medium-Z cargo in minute order exposure times.
- **Need to investigate more complex scenes (more complex backgrounds, additional vehicle components such as engines, differentials, etc. and smaller threat objects).**
- **Simulated results need more extensive experimental confirmation.**

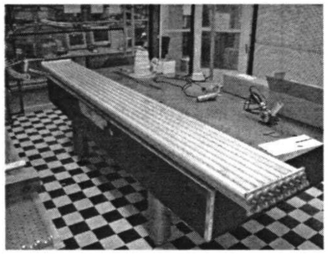
Los Alamos

Mid-Scale Demonstration Project

- **The first small scale experiment used 1x1 meter delay-line drift wire chambers. This technology does not scale up.**
- **We are currently building a 12 ft x 12 ft x 12 ft mid-scale detector project.**
  - Sized to radiograph the trunk of a car or small pickup truck bed.
  - Using 2 inch diameter, 12 foot long drift tubes packed into stackable modules of 16 tubes.
  - Along with muon radiography runs, this will be a test bed for other technologies.
- **We are looking at other technologies that may scale up better for full size detector stations.**

Los Alamos

Initial 12 foot Drift Tube Module



Los Alamos

Summary

- **The project is entering its third year.**
- **Have experimentally obtained radiographs of several objects.**
- **Simulation developed and validated.**
- **New reconstruction and visualization methods have been developed and are continuing to be refined.**
- **Mid-scale demonstration project under construction.**

Los Alamos

To Move Forward...

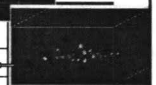
- **More simulation work (existing funds probably sufficient)**
  - Exposure time & detection ability vs. object size, placement and backgrounds.
  - What is reasonable smallest object size (SNM+shielding)?
  - Optimize analysis methods.
- **Mid-scale Experimental Demonstration**
  - Existing funding will not support momentum measurement.
  - Need additional ~500K to build fully functional unit.
- **Deployed Prototype (real vehicle traffic) if above is successful**
  - ~ $1M plus installation costs.

Los Alamos

Generalized results

110 130-kg spheres of F
0.8 kg of shielded Pu

Objects	Background: low	medium	high
U	1 min	1 min	3 min
Pig/Pu	1 min	1 min	4 min
Pu	2 min	2 min	6 min
Huge iron	1 min	1 min	1 min
Large iron	2 min	2 min	10 min
Backgr. only	1 min	1 min	2 min



55 130-kg spheres of Fe;
20 kg of U

11 tons of Fe; 5 kg of U

11 tons of Fe;
1700 kg Fe sphere